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APPLICATIONS OF CONTROL THEORY TO MACROECONOMICS

BY DAVID KENDRICK*

A survey of applications of control theory to macroeconomics is presented. Control theory has been applied to about fifty different macroeconomic models containing anywhere from one to more than three hundred equations, and including models of the economies of the United States, Canada, United Kingdom, West Germany, France, Belgium, Australia and the Netherlands.

A wide range of control theory methods has been applied to these models. Deterministic methods for both quadratic-linear and general nonlinear models have been used. Uncertainty has been introduced in the form of an additive noise to the systems equations and in the form of uncertainty about parameter values, and the models have been solved either with closed loop policies and/or open loop optimal feedback policies. Also, adaptive control procedures have begun to be used on the smaller models. In addition there have been a few applications of decentralized control techniques and of differential games.

In the past decade, a number of engineers and economists have asked the question: "If modern control theory can improve the guidance of airplanes and spacecraft, can it also help in the control of inflation and unemployment?"

Some of the results already available are displayed in Figure 1 in which inflation rates are plotted against unemployment rates. The origin of each arrow in the figure is the average inflation and unemployment rate experienced by the economy during the period studied. The authors of the study and the period covered appear above each arrow. The head of the arrow indicates the average inflation and unemployment rate obtained in a representative optimal control solution calculated by the authors. For the sake of comparison, the slope of the Phillips curve from the St. Louis FRB model [as displayed in Norman and Weatherby (74)] is also plotted. The location of the Phillips curve on the plot is arbitrary but its slope is as reported. If the controls solution provided unambiguous improvements over the actual path followed by the economy then the arrows would point toward their origin. Instead, the solutions show a movement toward less unemployment and more inflation. However, the nature of the trade-off is important.

On the one hand, it appears from Figure 1 that the optimal control solution could have brought substantial improvements at certain times, e.g., the Eisenhower years (see both the Friedman and Fair results), but in other periods, e.g., the Kennedy years, (Garbade and Pindyck results) the slopes are only slightly lower than for the Phillips curve. On the other hand, the results show that if an administration indeed prefers lower unemployment even at the cost of somewhat higher inflation rates, that result could be obtained using control methods. Or does it?

In fact, the authors of the studies cited above viewed their work as only a first step in the direction of providing an answer because their control solutions do not take adequate account of uncertainty and decentralization.

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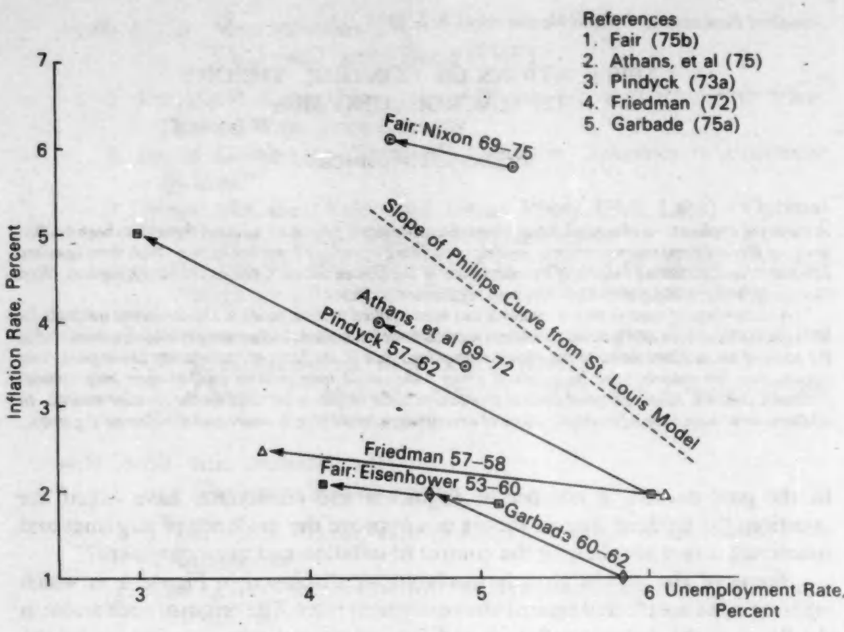

Figure 1 Deterministic Control Results

In the actual economy there is uncertainty about the parameters that represent behavioral responses in the economy, the state of the economy (values of current endogenous variables), future values of exogenous variables and shocks to the system, and the form of the model that governs responses in the economy. In the control solutions shown, only a very limited part of that uncertainty is taken account of. Also, decision-making powers in the actual economy are shared by the President, the Congress, and the Federal Reserve Board; in results shown, a single decision maker is assumed.

1. The Range of Control Theory Applications to Macroeconomics

In the last twenty years there have been approximately 60 applications to some 39 different macroeconometric models. They are listed in Appendix A in order of their size, and the names of those who used each model are listed under the model name.[1] Appendix B provides a similar listing for theoretical models. The diversity of sizes and the range of countries for which they have been used are readily apparent.

[1] When the model and the application are in the same article, a single listing is given.

2. Deterministic Results

The deterministic control problem may be written as: find $[u_t]_{t=1}^{N-1}$ to minimize

$$J = \phi_n(x_n) + \sum_{t=1}^{N-1} \phi_t(x_t, u_t) \tag{1}$$

subject to

$$x_{t+1} = f_x(x_t, u_t) \qquad x_0 \text{ given} \tag{2}$$

where (1) is the criterion function, (2) are the systems equations, the x's are state variables and the u's are control variables. For macroeconometric models the states are typically levels of consumption, investment, employment, price indices, etc. and the controls are government expenditure, taxes, and the money supply. So the system equations (2) consist of the reduced form of a macroeconometric model and the criterion function represent preference about rates of inflation and unemployment.

Many of the applications have used linearized systems equation and quadratic criterion functions and have written the problem as one of finding $[u_t]_{t=1}^{N-1}$ to minimize

$$J = (x_N - \tilde{x}_N)' W_N (x_N - \tilde{x}_N) + \sum_{t=1}^{N-1} \{(x_t - \tilde{x}_t)' W_t (x_t - \tilde{x}_t) + (u_t - \tilde{u}_t)' \Lambda_t (u_t - \tilde{u}_t)\} \tag{3}$$

subject to

$$x_{t+1} = Ax_t + Bu_t \qquad x_0 \text{ given} \tag{4}$$

where

x = state vector
u = control vector
$\tilde{x}$ and $\tilde{u}$ = desired values for states and control respectively
W, Λ = penalty weights on deviations of state and controls respectively from their desired paths.

Studies of this type are listed in the quadratic-linear column of Table 1. The nonlinear models of the form (1)–(2) are listed in the second column. Also, many of the second group of studies begin with (2) in implicit function form, i.e.,

$$g(x_{t+1}, x_t, u_t) = 0. \tag{5}$$

In fact since (5) may contain as many as two to three hundred equations, its solution is an important part of the nonlinear optimal control algorithms.

Certain themes recur frequently in these studies: the importance of proper timing and coordination of fiscal and monetary policy,[2] the importance of

[2] See for example Pindyck (73a) p. 140, Wall and Westcott (75) p. 16, and Craine, Havenner, and Tinsley (75) p. 12.

TABLE 1

DETERMINISTIC STUDIES

No. of Equations in Econometric Model	Quadratic-Linear	General Nonlinear
1–3	*Tustin (53) ‡Phillips (59) Holt (62) Shupp (75)	Cheng & Wan (72)
3–9	Bogaard & Theil (59) Theil (64) ‡Sandblom (70) ‡Thalberg (71a, 71b) Paryani (72) You (75)	Shupp (72) Healey & Summers (74) Sandblom (74) Norman & Weatherby (74) Healey & Medina (75)
10–25	Erickson, Leondes, & Norton (70) †Ho and Norton (72) Pindyck (72a) Erickson & Norton (73) Kaul (75)	Fair (74) Gupta, Meyer, Raines & Tarn (75)
25–80	van Eijk & Sandee (59) Theil (65) Friedman (72) Oudet (75)	Livsey (71) (74) Norman & Norman (73) Fitzgerald, Johnston & Bayes (73) Friedman & Howrey (73) Holbrook (74a) Rouzier (74) Craine, Havenner, Tinsley (75)
80–300	Fischer & Uebe (75)	Holbrook (73) (74b) Woodside (73) Ando, Norman, Palash (75) Athans *et al.* (75) Fair (75a, 75b)

* Theoretical models.
† Linear–linear.
‡ Classical rather than optimal control.

carefully choosing the criterion function,[3] the substantial alterations in the results when the length of the planning horizon (i.e., of *N*) is changed,[4] and the importance of choosing the solution procedure carefully when solving nonlinear models.[5]

[3] Livsey (71) p. 54.
[4] Garbade (75a) p. 180 and Athans *et al.* (75).
[5] Ando, Norman, and Palash (75), Fair (74) and Holbrook (74a).

3. Stochastic Studies

The stochastic control problem for reduced form models may be written in a quadratic-linear form as: find $[u_t]_{t=1}^{N-1}$ to minimize

$$J = E\{(x_N - \tilde{x}_N)' W_N (x_N - \tilde{x}_N) + \sum_{t=1}^{N-1} (x_t - \tilde{x}_t)' W_t (x_t - \tilde{x}_t) + (u_t - \tilde{u}_t)' \Lambda_t (u_t - \tilde{u}_t)\} \tag{6}$$

subject to systems equation

$$x_{t+1} = A(\theta_t)x_t + B(\theta_t)u_t + \xi_t \tag{7}$$

and measurement equations

$$y_t = Hx_t + \eta_t \tag{8}$$

where θ = a vector of unknown parameters, ξ = systems noise, η = measurement noise, and y = observation vector. Here it is assumed that the state vector cannot be observed directly but rather only through a noisy observer (8). The unknown parameters in A and B are stacked up in the vector θ. Three sources of uncertainty are included here: additive noise ξ_t, in the reduced form of the macroeconometric model, additive noises, η_t, in (8), and uncertainty about the parameter values, θ.

Studies that consider systems noise, ξ_t, only are listed in the first column of Table 2. If the problem is quadratic linear, the certainty equivalence theorem of Simon (56) and Theil (57) is applied and the problem is solved as a deterministic-quadratic linear control problem.[6] Garbade (75a, 75b) discusses a method to be used with nonlinear models and additive systems noise.

The second column of Table 2 contains studies that treat A and B as stochastic. For example the Cooper and Fischer (75) study examines the question of whether it is better to have a fixed growth rate rule for the money supply or to have a discretionary policy. The stochastic parameters are those of a lag distribution. Thus they address the Friedman question of whether or not a constant growth rate rule is better when the lags in the economy are long and uncertain. The more general case of unknown parameters is discussed by Chow (73a). Many of the methods used here are akin to those which engineers call open loop optimal feedback (OLOF). In these, the control may be cautious because of uncertainty about parameter values.

In the studies listed under "Dual" in Table 2, the parameters are unknown but it is assumed that they can be learned over time. The control has the "dual" purposes of achieving the desired targets and learning the parameters. However, this is in a sense a false dichotomy since the single goal of meeting the targets is the essential one and only that learning done in early periods helps in meeting the targets in later periods.

Four different adaptive control methods have been applied to macroeconometric models, Prescott (67), MacRae (72, 75), Abel (75) and Chow

[6] The Wall–Westcott method does not use the certainty-equivalence theorem. Also their model is linear in percent changes.

TABLE 2

STOCHASTIC STUDIES

No. of Equations in Econometric Model	Additive Noise	Parameter Uncertainty	Dual
1–3		Fisher (62) Zellner & Geisel (68) *Henderson & Turnovsky (72) Chow (73) *Turnovsky (73, 74a, 74b, 75a)	Zellner (66) (71) MacRae & MacRae (70) Abel (75) Chow (75)
3–9	Chow (72b) *Kareken, Muench, Wallace (73) Brito & Hester (74) *Phelps & Taylor (75) *Sargent & Wallace (75)	Burger, Kalish & Babb (71) Bowman & Laporte (72) Kendrick (73) Aoki (74a, 75a) Cooper & Fischer (75) Shupp (75)	Prescott (67) (71)
10–25	Bray (74) (75a) Pindyck & Roberts (74) Wall & Westcott (74, 75)	Kendrick & Majors (74) Walsh & Cruz (75)	Upadhyay (75)
25–80	Garbade (75a, 75b)		
80–300	Gordon (74)		

* Theoretical models.

(75a), and Upadhyay (75). It is not yet clear which of these methods (or some other method still untried) will prove to be superior in applications to macroeconometric models. So far none of the applications of adaptive control to macroeconomic models have included the errors in measurement, η_t. However, the updating of macroeconometric time series would indicate that the first data reported each quarter are indeed noisy; therefore, the use of this procedure could help in understanding the uncertainty which surrounds macroeconomic policy.

One of the attractive aspects of adaptive control is that it continually updates not only estimates of the x and the parameter vector θ, but also their convariances, Σ^{xx} and $\Sigma^{\theta\theta}$, as well. Thus, policymakers learn not only the expected performance of the economy associated with different policy measures but also the degree of uncertainty.

4. DECENTRALIZATION STUDIES

Though macroeconomic policy at least in the U.S. is definitely characterized by decentralization in decision making, there have so far been relatively few efforts to model this phenomenon. Those involving decentralized control are McFadden (69) and Aoki (75c), which contain three to nine equations. The models involving conflicting objectives are Kydland (73, 76) and Myoken (75a), which also contain three to nine equations, and Pau (73) and Pindyck (76), which contain ten to twenty-five equations. The model in Myoken is theoretical only.

TABLE 3

DECENTRALIZATION STUDIES

No. of Equations in Econometric Model	Decentralized Control	Conflicting Objectives
1–3		
3–9	McFadden (69) Aoki (75c)	Kydland (73) (76) *Myoken (75a)
10–25		Pau (73) Pindyck (76)
25–80		

* Theoretical.

5. FUTURE RESEARCH

The answer to the original question of this paper remains elusive. Efforts are now underway to include both uncertainty and decentralization, but only a bare beginning has been made. So the central direction of future research will be the application of methods of adaptive control and game theory to macroeconometric models of increasing size.

Some other areas worth further research effort are listed below:

(a) The Federal Reserve Board can make monetary policy decisions fairly quickly. However, fiscal decisions are made by the President, but must then go to Congress, and back to the President. No control theory application has yet taken account of the difference in timing between the policy-making actions.

(b) The measurement errors in (8) above have not yet been systematically included and should be. This should include not only the fact that macroeconomic time series are characterized by different degrees of uncertainty, but also a careful consideration in the timing of the availability of data.

(c) Related to point b, above, are the differences in the way data are collected: most data are quarterly, but some are daily, weekly, or monthly. The problem raised is how best to integrate monthly or weekly models with quarterly ones.

(d) The response of agents to the announcement of feedback control policy needs to be considered because the mere announcement may change the behavior of agents and thereby render the policy suboptimal, viz. Kydland and Prescott (75).

(e) Policy decisions about macroeconomics are highly visible and much debated in the political arena. Consequently, policy models used in this field cannot be divorced from but rather must be enriched by the political environment which surrounds these decisions. For an interesting example see Fair (75b).

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APPENDIX A

Numerical Macroeconometric Models Used in Control Theory Applications

Name (Date)	Country	Periodicity[a]	Estimation Period	Behavioral Equation	Identities	Systems Equations	Criterion[b]	States	Control
1. Zellner & Geisel (68)	US	A	1921–29	1		Linear	Quadratic		
2. Chow (74)	US	A	1953–72	1	0	Linear	Quadratic	1	2
3. Shupp (75a)	US	Q	67III–71II	2		Log-Linear	Quadratic		
4. Abel (75)	US	Q	54I–63IV	2	0				
(a) Abel (75)						Linear	Quadratic	2	2
(b) Chow (75a)									
5. Holt (62)		Q		2	1	Linear	Quadratic		
6. Phillips (54)						Linear	None		
7. Goodwin (51)				3	1				
8. Klein (50)	US	A	1921–40	6		Linear			
(a) Theil (64)						Linear	Quadratic		
(b) Bogaard & Theil (59)						Linear	Quadratic		
9. St. Louis FRB Andersen & Carlson (70)	US	Q	55I–71II	4	3				
(a) Burger, Kalish & Babb (71)						Nonlinear	Quadratic		
(b) Cooper & Fischer (75)						Nonlinear	Quadratic	8[c]	2
(c) Norman & Weatherby (74)						Nonlinear	Quadratic	2	1
(d) Bowman & Laporte (72)									
(e) Healy & Summers (74)									
(f) Healy & Medina (75)									
10. McFadden (69)				4	4	Linear	Quadratic		
(a) McFadden (69)									
(b) Kydland (73) (76)				4	4	Linear	Quadratic		
11. Kmenta-Smith (73)	US	Q	54I-63IV	5	3				
(a) Paryani (72)						Linear	Quadratic	5	3
12. Sandblom (70)				8		Linear	None		
(a) Thalberg (71a, 71b)				8		Linear	None		
13. Chow (67)	US	A	1921–40 1948–63	4	5				

APPENDIX A (Continued)

Numerical Macroeconometric Models Used in Control Theory Applications

Name (Date)	Country	Periodicity[a]	Estimation Period	Behavioral Equation	Identities	Systems Equations	Criterion[b]	States	Control
(a) Chow (72b)						Linear	Quadratic		
(b) Prescott (67) (71)						Linear	Quadratic		
(c) Kendrick (73)						Linear	Quadratic		
(d) You (75)						Linear	Quadratic		
(e) Fair (74)						Linear	Quadratic		
14. Shupp (72)	US	Q		8	1	Nonlinear	Nonlinear		
15. Pau (73)	Denmark	A				Nonlinear	Nonlinear	8	25
16. Pindyck	US	Q	55I–67IV	9	2				
(a) Pindyck (72a, b; 73a, b)						Linear	Quadratic	28	3
(b) Kendrick & Majors (74)						Linear	Quadratic	30	3
(c) Walsh & Cruz (76)						Linear	Quadratic	30	3
(d) Pindyck (76)						Linear	Quadratic game	28	3
17. Laidler (73)									
(a) Gupta, Meyer, Raines & Tarn (75)	US	Q				Nonlinear	Nonlinear		
18. Dept. of Finance Model	Canada	A		8	5				
(a) Ho & Norton (72)						Linear	Linear	11	3
19. Kaul (75)		A		15		Linear	Linear		
20. Erickson, Leondes & Norton (70)	US	Q		5	11				
(a) Erickson, Leondes & Norton (70)						Linear	Quadratic		
(b) Erickson & Norton (73)									
21. FRB Monthly Model Thompson, Pierce & Perry (74)									
(a) Pindyck & Roberts (74)		M		10	8	Linear	Quadratic	46	15
22. Fair (70)	US	Q		14	5				
(a) Fair (74)						Nonlinear	Nonlinear		
23. Livsey (71)	UK	Q	57I–66IV	8	11	Nonlinear	Nonlinear		

APPENDIX A (Continued)

NUMERICAL MACROECONOMETRIC MODELS USED IN CONTROL THEORY APPLICATIONS

Name (Date)	Country	Periodicity[a]	Estimation Period	Behavioral Equation	Identities	Systems Equations	Criterion[b]	States	Control
24. PREM1	UK	Q							
Wall & Westcott (74)									
(a) Wall & Westcott (74)			55I–73II	11		Linear in	Quadratic		
(b) Bray (74) (75a)			55I–73II	15	10	Percent	Quadratic		
(c) Wall & Westcott (75)			55I–73II	13	12	Change	Quadratic		
25. Rouzier (74)	Belgium	A	1953–74	16	10	Non-linear	Quadratic	4	2
26. Central Planning Bureau (56)	Netherlands	A		27		Linear	Linear		
(a) van Eijk & Sandee (56)									
27. Klein (69) & Norman (69)									
(a) Norman & Norman (73)	US	A	1929–64	27		Nonlinear	Quadratic		
28. Bogaard & Barten (59)	Netherlands	A		12	28				
(a) Theil (64)						Linear	Quadratic	4	5
(b) Theil (65)						Linear	Quadratic	4	5
29. Garbade (75a)	US	Q	47I–69IV	31	12	Nonlinear	Nonlinear	54	6
(a) Garbade (75a, b)									
30. MINNIE	US	Q		21	40				
Battenberg, Enzler & Havenner (74)									
(a) Craine, Havenner & Tinsley (75)				21	40	Nonlinear	Quadratic		
31. Michigan Model	US	Q							
Hymans & Shapiro (73)									
(a) Holbrook (74a)						Nonlinear	Quadratic	>61	3
32. NIF-2	Australia	Q							
Higgins & Fitzgerald (72)									
(a) Fitzgerald, Johnson & Bayes (68)				26	41	Nonlinear	Piecewise Quadratic		3

APPENDIX A (Continued)

NUMERICAL MACROECONOMETRIC MODELS USED IN CONTROL THEORY APPLICATIONS

Name (Date)	Country	Periodicity[a]	Estimation Period	Behavioral Equation	Identities	Systems Equations	Criterion[b]	States	Control
33. Wharton Model									
Evans & Klein (68)	US	Q	48I–64IV			Nonlinear			
(a) Friedman (72)				47	29	Linearized	Piecewise Quadratic		
34. STAR	France	A		77		Nonlinear			
Boulle, Bayer, Mazier & Olive (74)									
(a) Oudet (76)						Linear	Quadratic	31	10
35. Fair (75a)	US	Q		82		Nonlinear	Nonlinear		
(a) Fair (75)									
(b) Fair (76)									
36. Athans *et al.* (75)	US	Q	1954I–1973IV	37	46	Nonlinear	Quadratic		20
37. Krelle (74)									
(a) Fischer & Uebe (75)	W. Germany	A	1955–71						
38. FMS	US	Q		≈200					
Ando, Modigliani & Raashe (72)									
(a) Ando, Norman & Palash (75)						Nonlinear	Quadratic		
(b) Palash (75)						Nonlinear	Quadratic		
39. Bank of Canada RDX2	Canada	Q		260					
Heliwell *et al.* (71)									
(a) Holbrook (73) (74b)						Nonlinear	Quadratic		
(b) Woodside (73)						Nonlinear	Quadratic		
40. Data Resources, Inc.	US	Q		168	153	Nonlinear			
(a) Gordon (74)						Nonlinear	Quadratic		

[a] A = annual; Q = quarterly; M = monthly.
[b] "Nonlinear" here means nonquadratic and nonlinear.
[c] Number of states used in the feedback.

APPENDIX B

THEORETICAL MACROECONOMETRIC MODELS USED IN CONTROL THEORY APPLICATIONS

Name (Date)	Country	Periodicity	Estimation Period	Behavioral Equation	Identities	Systems Equations	Criterion	States	Control
1. Henderson & Turnovsky (72)									
2. Kareken, Muench & Wallace (73)				5	0	Linear	Quadratic		
3. Mundell (65)									
(a) Cheng & Wan (72)						Linear	Minimum time	2	1
4. Myoken (75a)									
5. Phelps & Taylor (75)				3	3	Linear	Quadratic		
6. Sargent & Wallace (75)				5	0	Linear	Quadratic		
7. Shupp (76)				5	0	Linear	Quadratic		
8. Turnovsky (73) (74a) (74b) (75a)									
9. Zellner (66)									